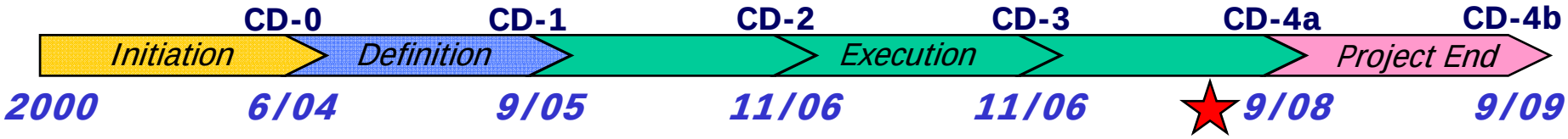
TEAM – Remote Operation

Project status

P. Denes
Project Manager

TEAM

Transmission Electron Aberration-corrected Microscope



Four Years Later: An Interim Report on
Facilities for the Future of Science:
A Twenty-Year Outlook
August 2007

www.science.doe.gov

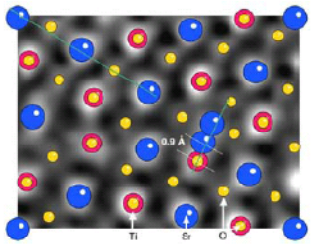
Priority: Tie for 7

Transmission Electron Aberration Corrected Microscope (TEAM)

Electron microscopes were among scientists' first tools for probing matter at the nanoscale. Yet as nanoscience has advanced, the performance requirements for electron microscopes have become ever more demanding. Achieving ever more precise resolution on ever smaller scales requires overcoming inherent aberrations in the operations of these devices that undermine performance. This in turn requires dramatic breakthroughs in electron optics, mechanics, and electronics—breakthroughs that are beyond the reach of any single university or laboratory.

Five national laboratories have teamed together to develop a new generation of electron microscope with the capability of sub-nanometer resolution. Based at Lawrence Berkeley National Laboratory, the team includes researchers from Argonne National Laboratory, Brookhaven National Laboratory, Oak Ridge National Laboratory, and the Frederick Seitz Materials Research Laboratory at the University of Illinois at Urbana-Champaign.

The TEAM microscope will have multiple applications to materials science and nanoscience to help scientists design new materials for everything from more efficient automobiles to stronger, more energy-efficient buildings, and new ways of harvesting energy.



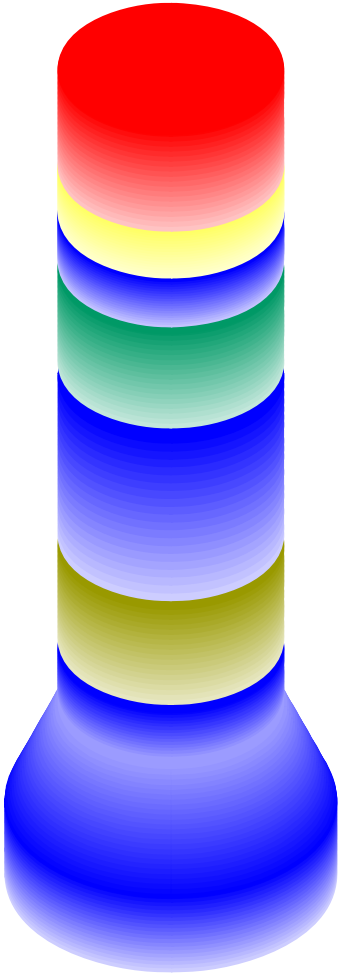
Atomic structure of a Sigma 13 grain boundary in SrTi03. TEAM will be the first of a new generation of intermediate-voltage electron microscopes capable of developing a much more fundamental understanding of materials by achieving resolution near 0.05 microns.

Update: The TEAM project is proceeding as planned. TEAM has an approved Performance Baseline, and fabrication of an aberration-corrected electron microscope at Lawrence Berkeley National Laboratory for the materials and nanoscience communities will proceed on schedule, with an initial instrument available to users in FY 2008 and fabrication of the final instrument completed in FY 2009.

- Mission Need for the TEAM project was approved in June 2004, and the performance baseline was established in November 2006 along with the approval for start of fabrication.
- The TEAM instrument is expected to attain spatial resolution of 0.05 nm. Beyond sheer resolution, expected and planned improvements in sample manipulation, in-situ capabilities, signal-to-noise ratio, mechanical and electrical stability, and other aspects are also important instrumentation developments. They will greatly expand the capabilities of TEAM over existing electron microscopes, providing scientists with a world-leading tool for materials science and nanotechnology research.

TEAM Project Deliverable

- Key Technical Specifications:
  - 80-300 keV
  - 0.5Å performance
  - 0.1 eV δE
  - $\beta \geq 3x10^9$ A/cm^2/sr
- Enhance capabilities of DoE Nanocenters
- On time and on budget



High-Brightness Electron Gun

Monochromator

Condenser

Improved C_3 / C_5 corrector

Objective lens
5 mm gap
Novel stage

C_S / C_C corrector

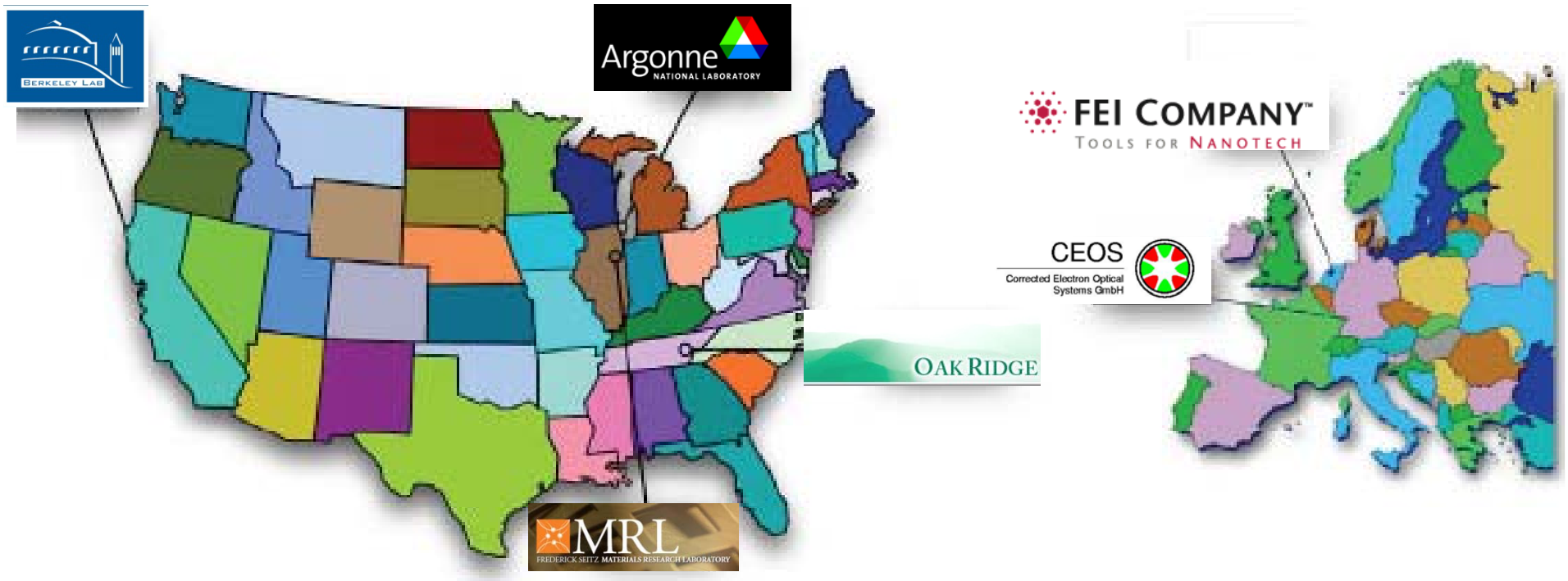
Spectrometers

Projectors

Detectors

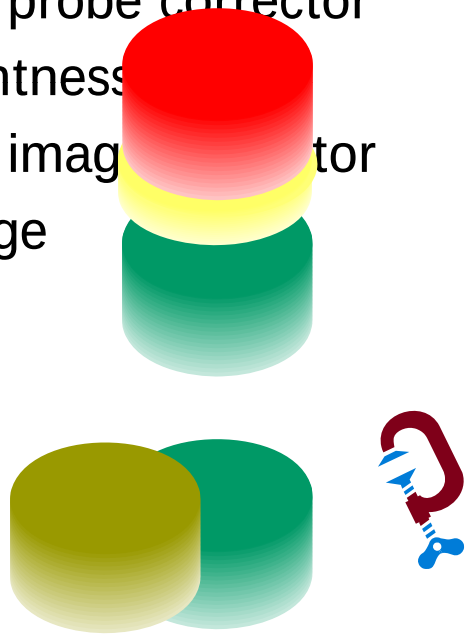
In PEP

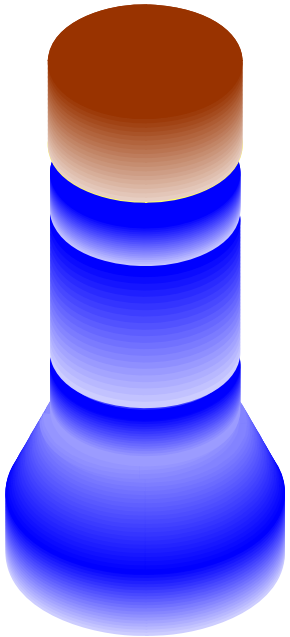
TEAM Players



TEAM is an Integration Project

- Start with the best “platform”
- Monochromated and double-corrected
- Improved probe corrector
- High-brightness
- Improved imag tor
- TEAM Stage

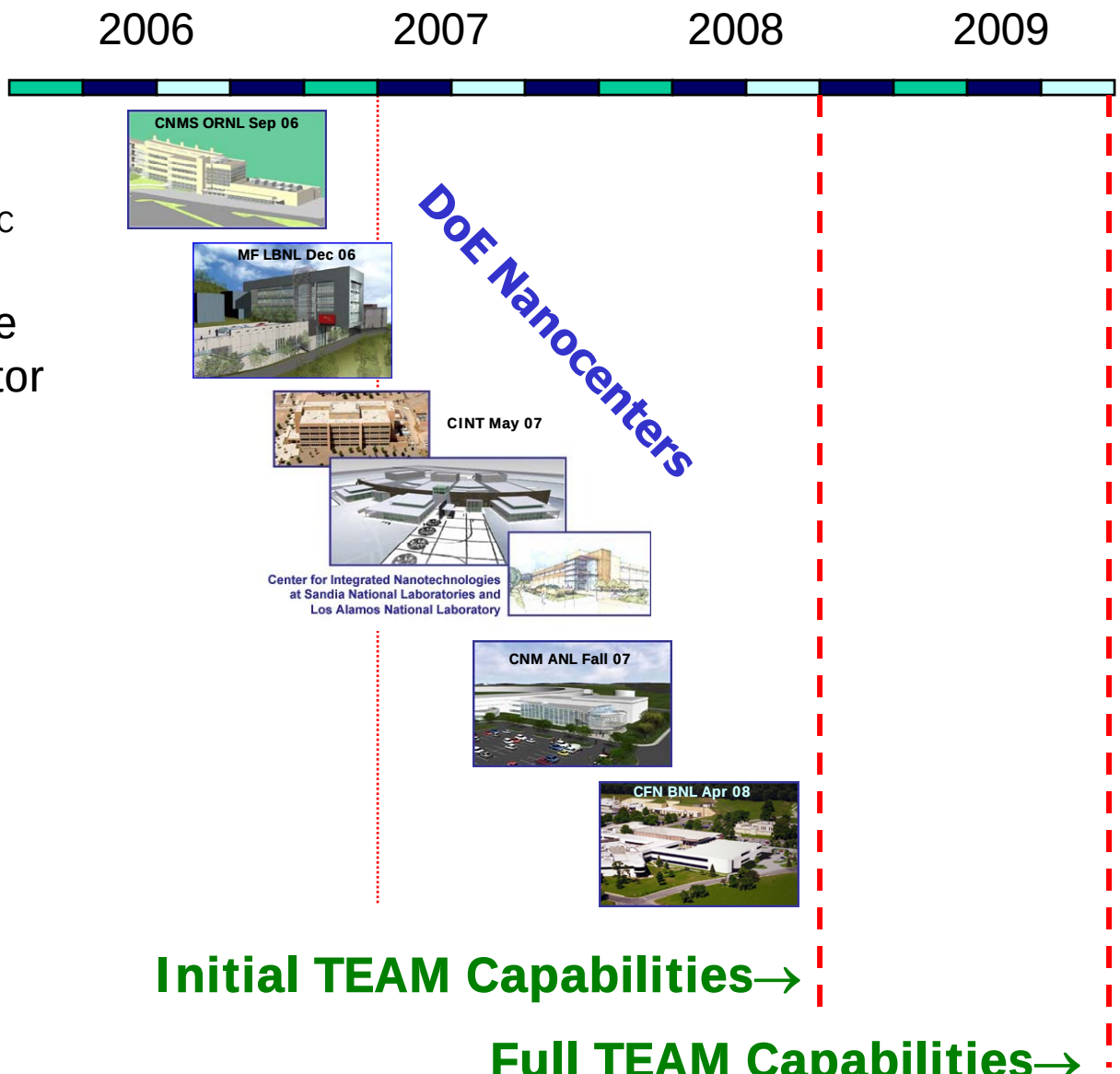




Staged Approach

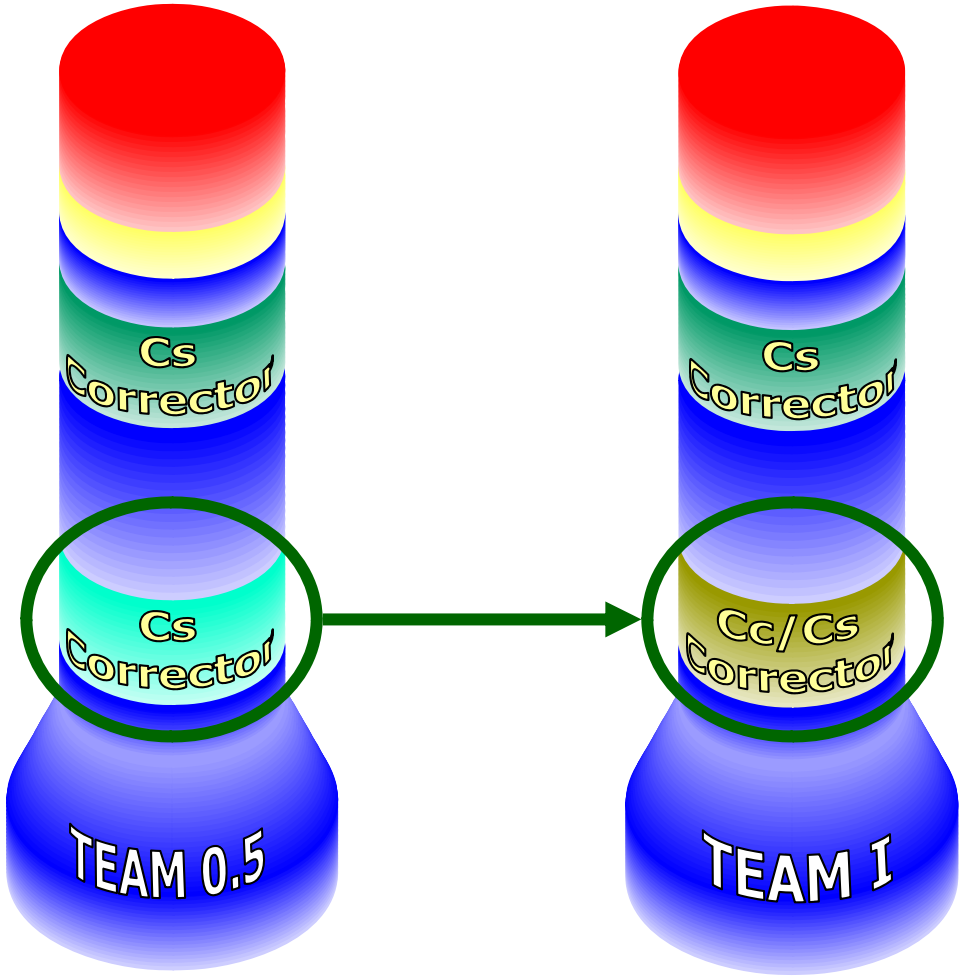
- Longest lead item is the C_C corrector
- *Most* of TEAM goals can be achieved *before* C_C corrector is ready

⇒ Staged approach



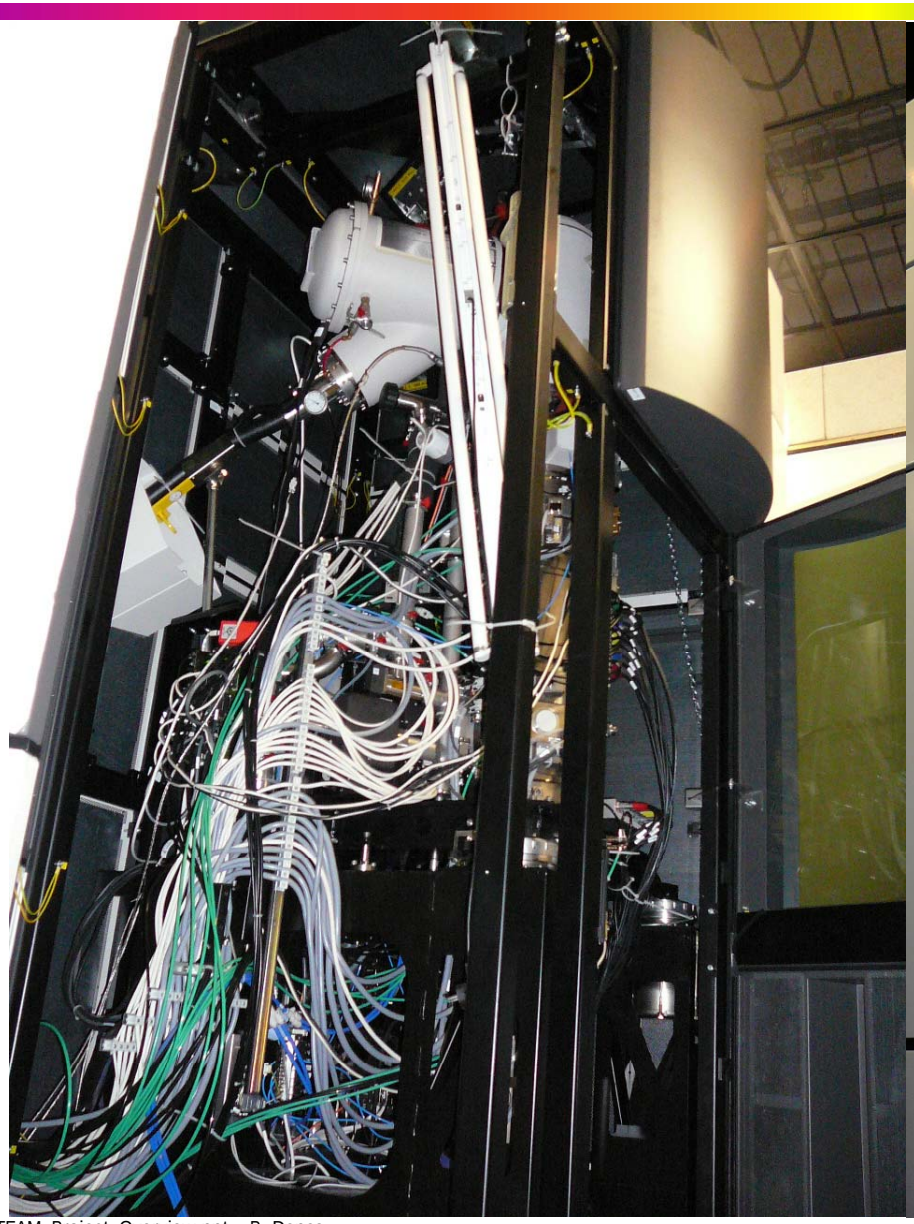
Staged Approach

- TEAM 0.5
  - Delivery Dec. ‘07
  - Early start: Spring ’08
  - CD-4a: Sep. ’08
  - End lease once TEAM I is running
- TEAM I
  - Delivery Mar. ’09
  - CD-4b: Sep. ‘09



TEAM 0.5 ≈ TEAM I – C_C corrector

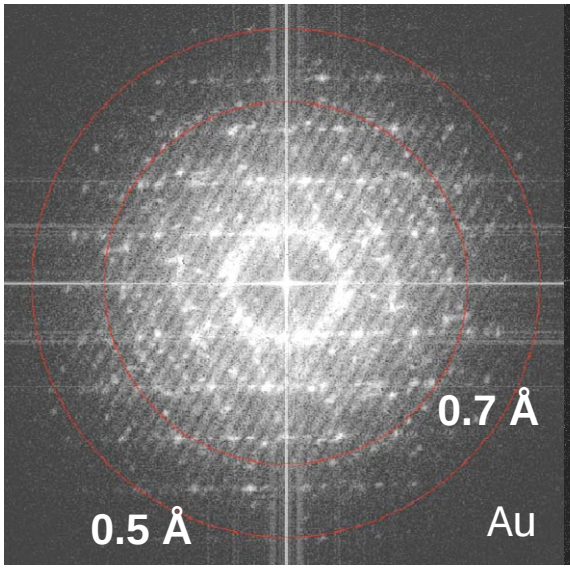
TEAM 0.5



Technical Goals of Project Achieved

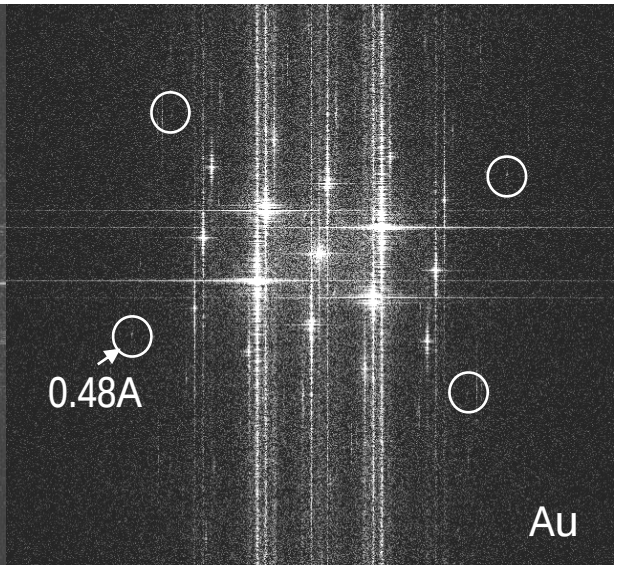
Observed on TEAM 0.5

Aug. ‘07



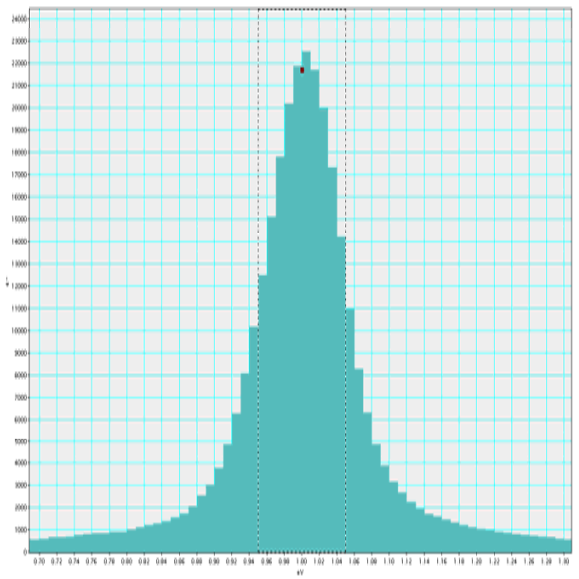
0.5Å TEM
Young’s Fringes

Aug. ‘07



0.5Å STEM
Fourier Components

Oct. ‘07



0.1 eV δE

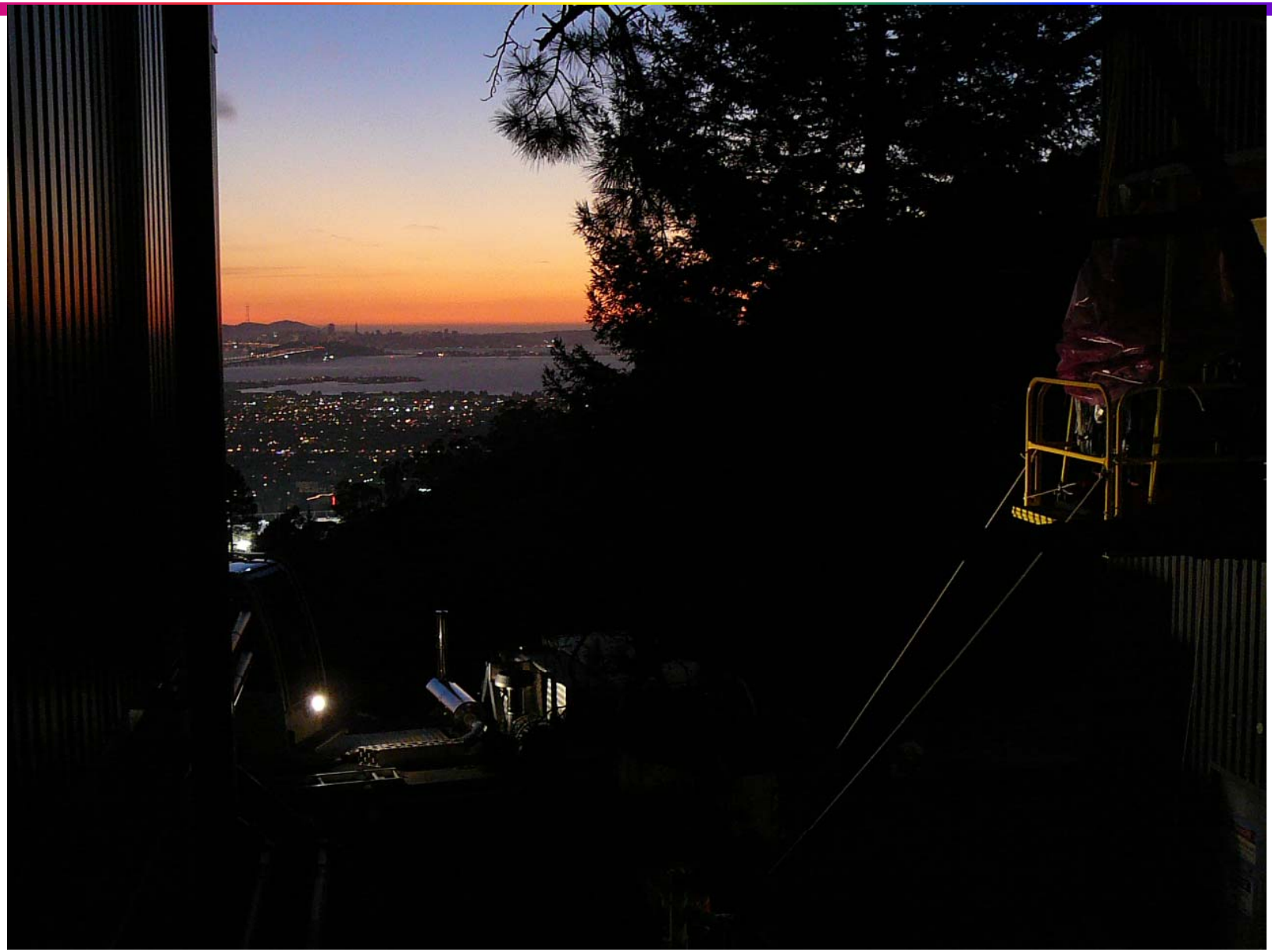
β = 3-6x10^9 A/cm^2/sr (tunable for different ΔE)

Final Factory Acceptance Test (“CWAT”) Oct. ‘07

TEAM 0.5 Installation in 72A

LBL is on a hill

TEAMset



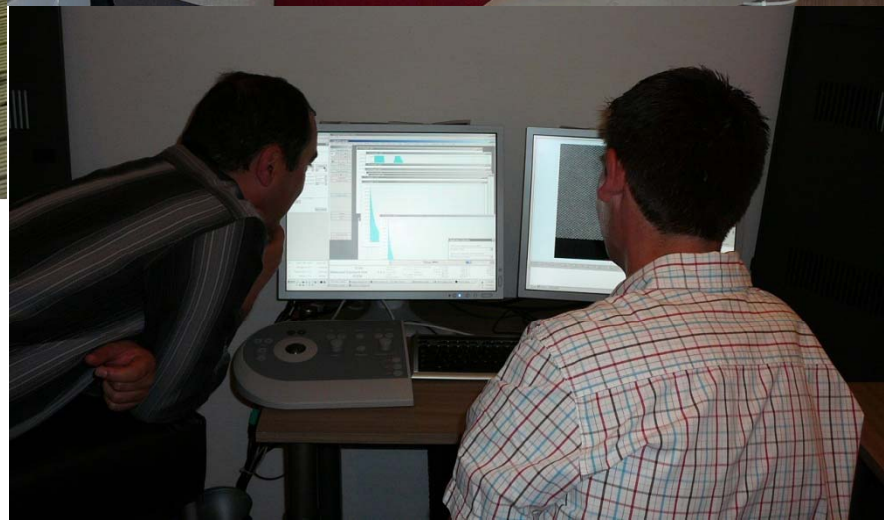
TEAM I Factory Acceptance – May 2008

(from left to right)
Standing: Michiel van der Stam, Peter Denes (LBNL), Sebastian von Harrach, Hans van Lin, Rolf Erni (LBNL), Veli Altin, Peter Tiemeijer
Front Row: Guido Knippels, Sorin Lazar, Annette Kolodzie, Maarten Bischoff
Not on picture: Bert Freitag, Reinout Hartong, Pleun Dona, Ab Visscher, Casper Smit

The TEAM 1 Project Team is proud of the 0.5 Å achievement on its Titan³ 80-300 !!

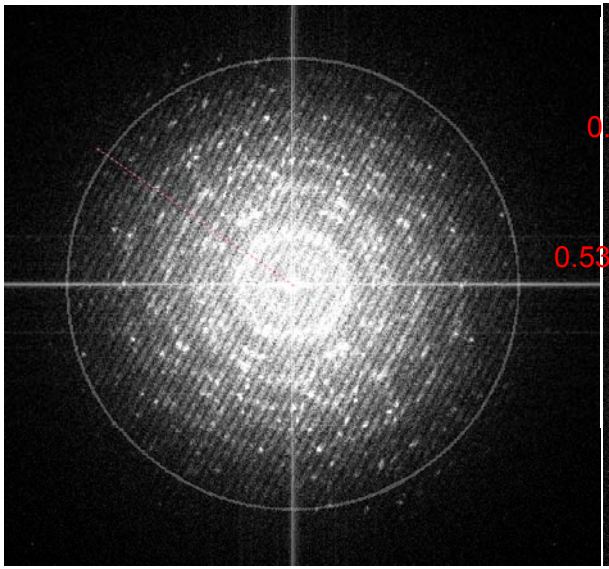
FEI COMPANY™
TOOLS FOR NANOTECH

May 13 – 16, 2008
FEI Eindoven, The Netherlands

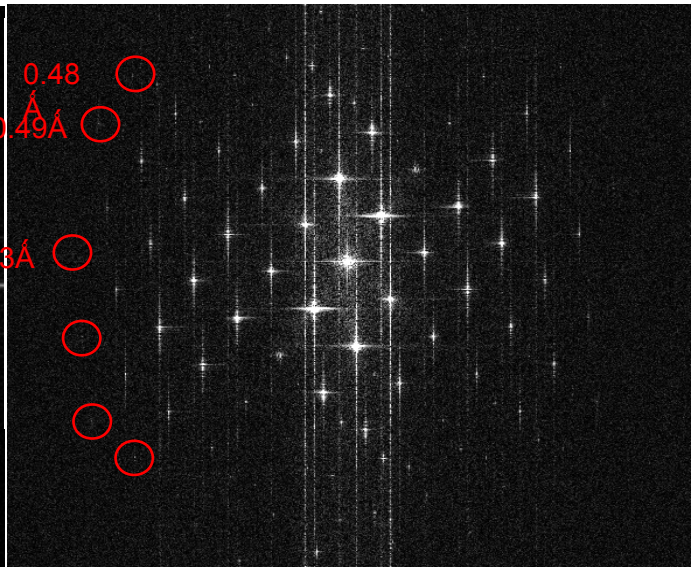


TEAM I Performance

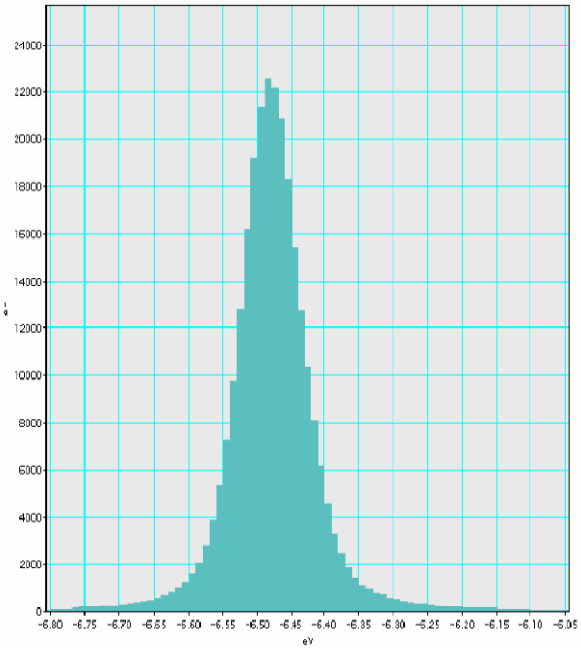
Observed on TEAM I



0.5Å TEM
Young's Fringes



0.5Å STEM
Fourier Components



0.1 eV δE

β = 3-6x10^9 A/cm^2/sr (tunable for different ΔE)

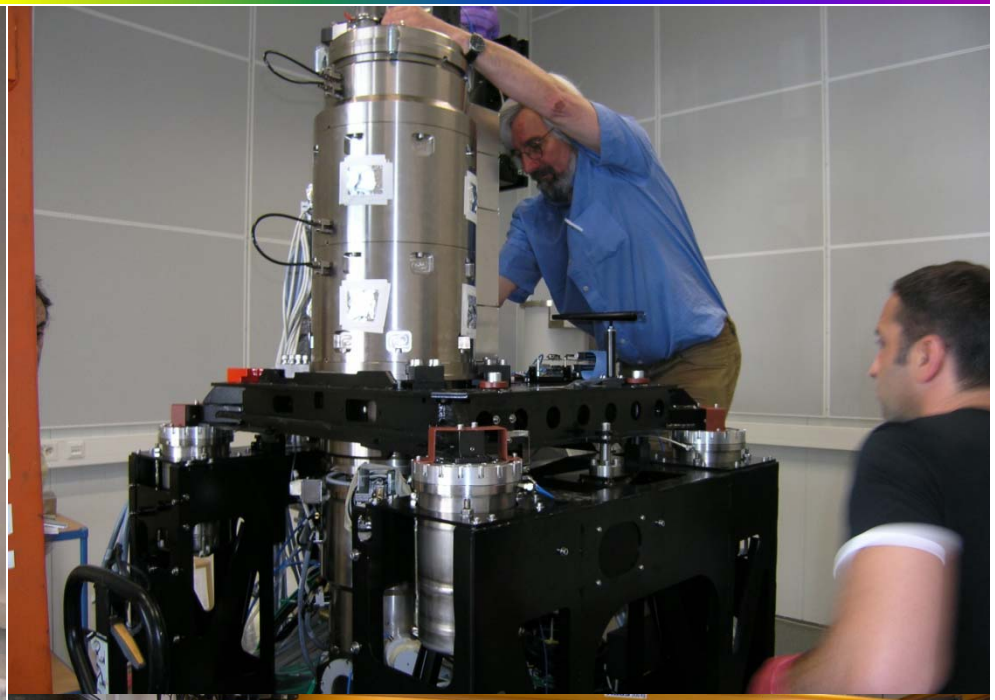
Final Factory Acceptance Test ("CWAT") May. '08

C_C Correction

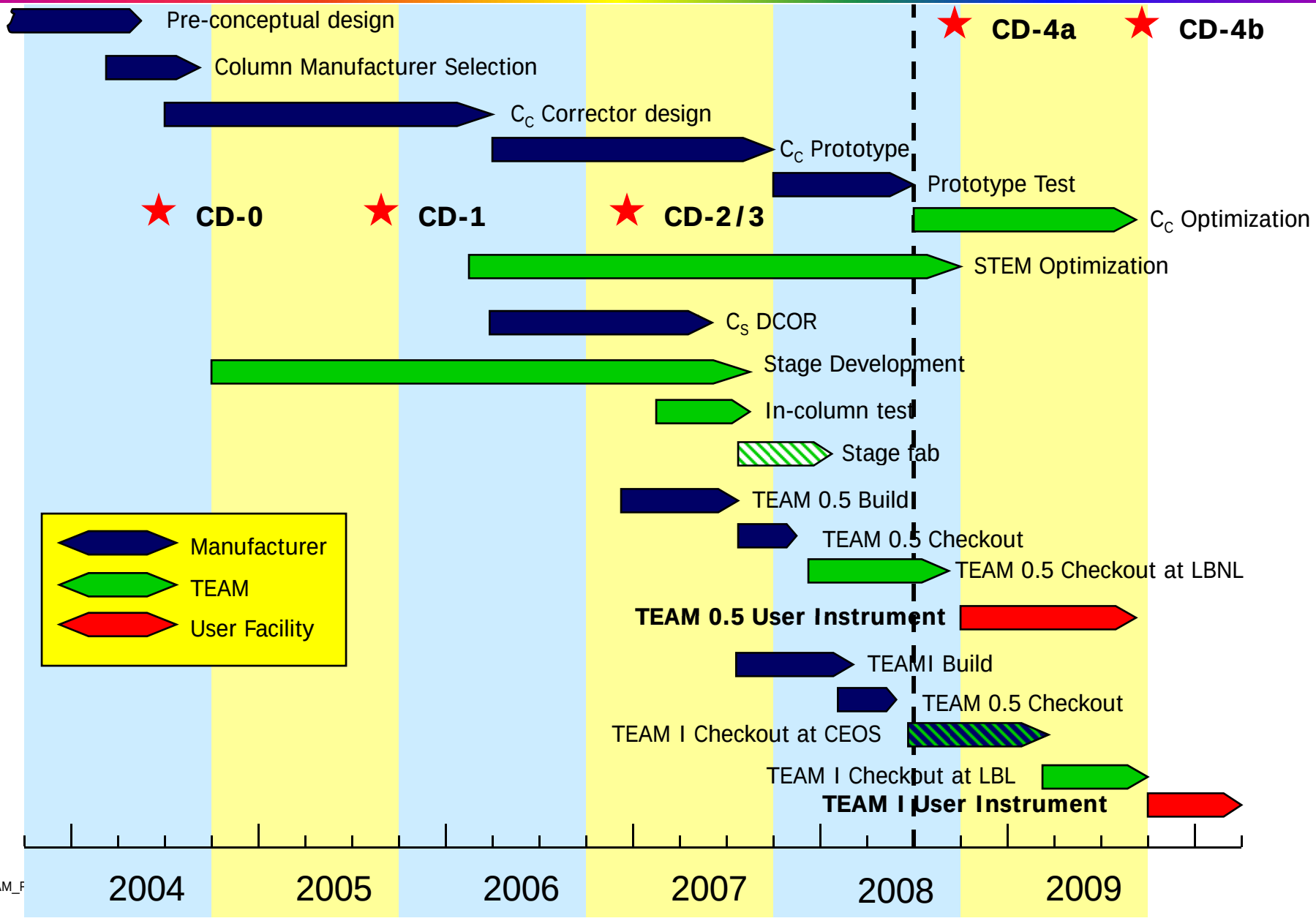
Prototype corrector → Titan 0 (Jan '08)

- First tests – 200 keV
- Apr '08 – obtain 1Å information limit (symmetric)
- Can increase energy width to 30 eV and still maintain 1Å resolution
- 4Å resolution with 860 eV energy width
- Value of C_C factor 2 better than specification

TEAM I Buildup with C_c Corrector



Summary Timeline



Summary

- Project is mature, and nearing completion
  - Key technical goals met
  - CD-4a (start of TEAM 0.5 as a user facility) this FY
  - TEAM I even better than TEAM 0.5
- "Beyond resolution"
  - C_C correction, longest lead item, works
  - Final C_C corrector being integrated into TEAM I now
  - TEAM stage – towards goal of tomography and in-situ
  - TEAM detector – towards goal of in-situ and sensitivity
  - TEAM software – towards all goals
  - TEAM Remote

In the beginning …

Risk Analysis and Contingency

- Good old days: Best guess - project costs $X. DOE sends $X. Whoops! Project really costs $X+$\Delta$X, so DOE sends an extra $$\Delta$X
- Modern times: Best guess - project costs $X. DOE allocates $X and makes it very clear that it will not send 1¢ more.
  - By analyzing the (cost and schedule) risk of all of the items, determine that the most probable cost risk is $$\Delta$X.
  - Keep $$\Delta$X (or $$\Delta X+\Delta^2 X$) in a special reserve called "contingency" which has special rules on how it can be used
  - $X-$\Delta$X is now "available" to the project

Today

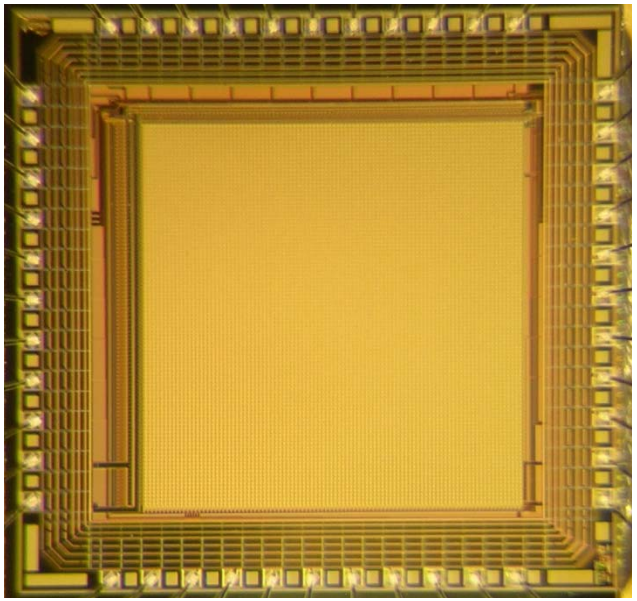
- Technical objectives of project have been met
  - 0.5 Å spatial resolution in TEM and STEM
    - (both in TEAM 0.5 with UT lens and TEAM I with ST lens)
    - TEAM I is a better microscope than TEAM 0.5 (sigh of relief!)
  - 0.1 eV energy resolution
  - High brightness gun
- Critical path was always the C_C corrector
  - Now demonstrated: C_C correction works!
  - (Not yet demonstrated that it works to 0.5 Å)
- $\rightarrow$ we have "earned contingency" (it wasn't as bad as it could have been) $\rightarrow$ genuine calls on contingency and "enhancements"
  - Stage (produce, various β modules)
  - Software (relevant for today's discussion)
  - Detectors
  - Development column (for stage, software, detectors)
  - Additional C_C corrector technique development

Two TEAM-inspired Additions

Stage

- Unlike conventional stage
- Needs own software interface
- “Connect” to microscope operating system

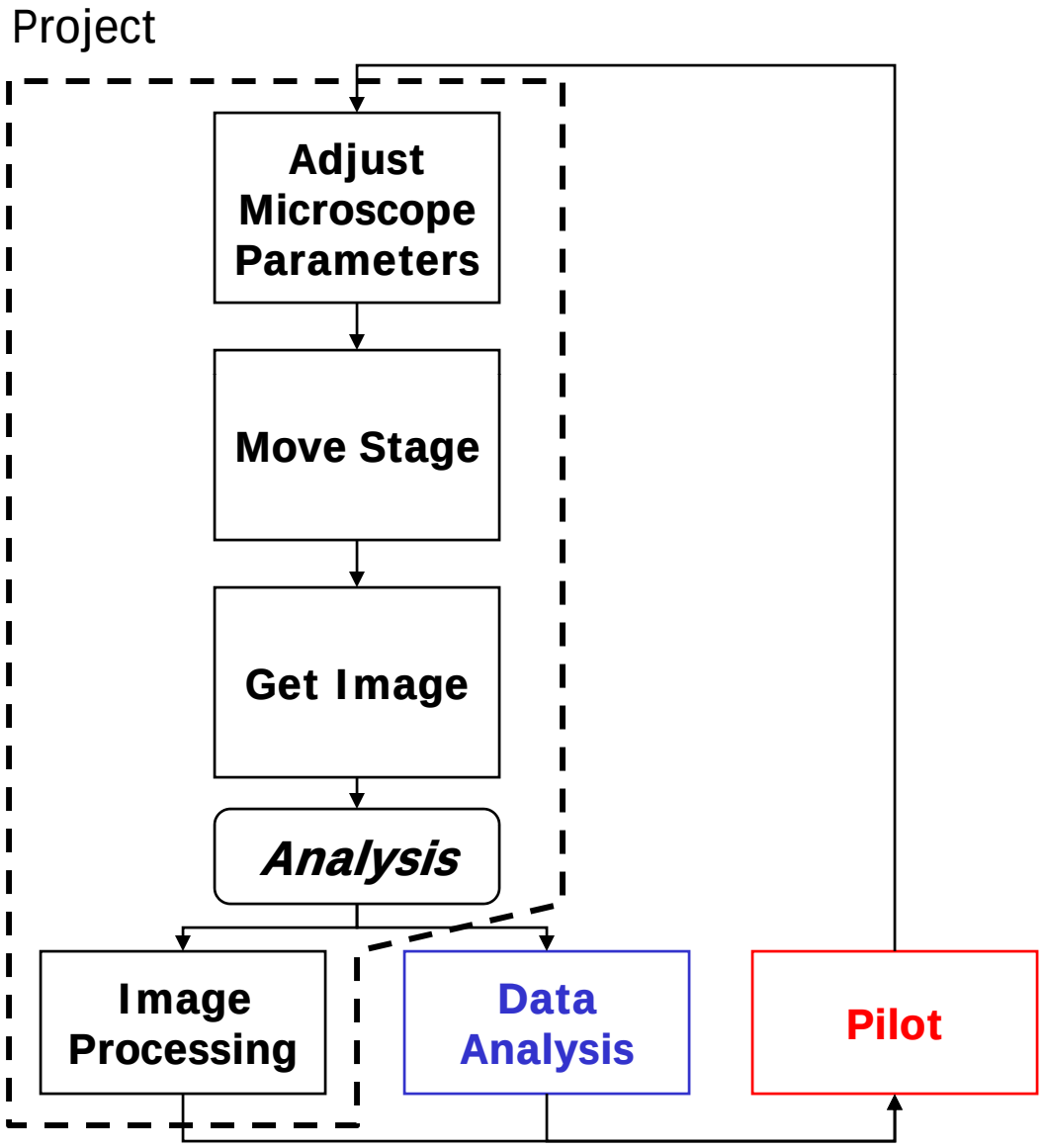
Detectors



- 400 Megapixels/sec
- In-situ triggered stop experiments

Software

- Parameter adjustment and image acquisition: primarily TEM server, some DM
- You'll hear more about this



"Issues"

- Remote operation "modalities"
  - Who? (How authenticated)
  - Support@Berkeley – what does this entail
- Remote operation "nuts and bolts"
  - ESnet
  - Hardware (paddles)
  - Software (simple operation or apps?)
- …